

Metal/GaN Schottky barriers characterized by ballistic-electron-emission microscopy and spectroscopy

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Ballistic-electron-emission microscopy (BEEM) and spectroscopy have been used to characterize the Pd/GaN and Au/GaN interfaces. BEEM spectra yield a Schottky barrier height for Au/GaN of ~ 1.05 eV that agrees well with the highest values measured by conventional methods. For both Pd and Au, a second threshold is observed in the spectra at about 0.2 - 0.3 V above the first threshold. Imaging of these metal/GaN interfaces reveals transmission in nearly all areas, although the magnitude is small and spatially varies. Attempts to perform BEEM measurements on other GaN material have resulted in no detectable transmission in any areas, even at voltages as high as 3.5 V.

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Recent progress in the growth of GaN and related nitrides has stimulated interest in the use of these materials for short-wavelength light-emitting diodes (LEDs), high-electron-mobility transistors (HEMTs), and metal-semiconductor field-effect transistors (MESFETs). Moreover, GaN exhibits stability at high temperatures and a general unreactivity in caustic environments. However, the lack of a suitable lattice-matched substrate for epitaxial growth has hindered the achievement of low defect densities in GaN. Shrinking device dimensions also emphasize as never before the role of defects in device uniformity. As one example, optimization and reproducibility of device characteristics requires stable, high-quality Schottky contacts to these materials. Unfortunately, electronic properties of interfaces to GaN and its alloys are still not well understood, and macroscopic electrical characterization is hindered by the presence of defects.

Ballistic-electron-emission microscopy [1] (BEEM) was developed from scanning tunneling microscopy [2] (STM) as a high-resolution, non-destructive probe of buried interfaces and hot-carrier transport. The high spatial resolution of BEEM derives from the high spatial resolution inherent in STM and allows the characterization of interfaces on a nanometer scale. An energy spectroscopy of interface electronic properties may be performed, and these features may be imaged directly by scanning the STM tip. BEEM provides a local measurement of Schottky barrier height and is also sensitive to other details of interface band structure [1]. This paper describes the application of BEEM spectroscopy and imaging to a characterization of metal/semiconductor Schottky contacts to GaN.

The GaN layer used in this work was grown by metal-organic chemical vapor deposition (MOCVD) on a (0001) oriented sapphire substrate using trimethyl gallium and ammonia as source materials and disilane to supply the donor dopant. A low temperature nucleation layer was first grown, followed by a higher temperature GaN layer. The

GaN growth temperature was 1040° C as measured by optical pyrometer. The one-hour growth at a pressure of 150 T produced a 2.2 μm -thick GaN layer. Room temperature carrier concentration was $1.2 \times 10^{17} \text{ cm}^{-3}$ as determined by Hall measurement, and measured electron mobility was 534 cm^2/Vs . The measured full width at half-maximum of the (004) X-ray peak was 284 arc-seconds. Ti/Al ohmic contacts were processed by rapid thermal annealing in a nitrogen environment at 900° C for 90 s.

Samples were divided into 4 mm squares. Metallization was preceded by transfer into a nitrogen-purged glove-box for chemical cleaning, where the sample was spin-etched [3] using 1:10 HCl:ethanol. For the case of Au contacts, the sample was then directly transferred into the load-lock attached to the evaporation chamber. The Au layer was deposited at a pressure of 2×10^{-9} T. For Pd contacts, the sample was transferred in a nitrogen-filled container to another glove-box attached to a second evaporation chamber. Pd was deposited at a pressure of approximately 1×10^{-7} T. After metal deposition the sample was moved to the STM, also located in a nitrogen glove-box. BEEM measurements were performed at room temperature unless otherwise stated. Additional sample fabrication and measurement details have been presented elsewhere [4].

The first attempts to perform BEEM measurements on GaN were unsuccessful, initially due to difficulty in forming low-leakage Schottky barriers. A decrease in contact area and an increase in material quality resulted in low-leakage contacts; however, most of the GaN layers did not produce measurable BEEM current (down to a detection level of several fA). Many BEEM samples were made using different surface treatments, including hot aqua regia and HCl, and the possibility of a defective surface GaN layer was investigated by etching a fraction of the GaN away using hot KOH. Au, Pd, and Pt were used for

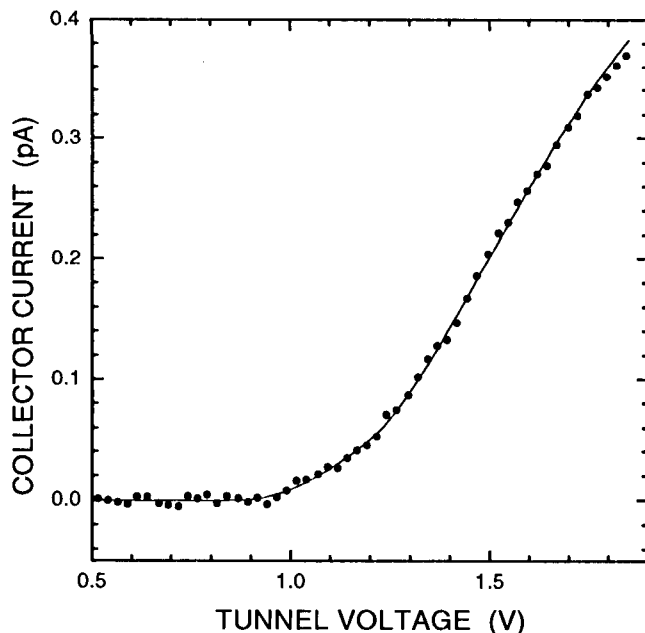


FIG. 1. BEEM I_c -V spectrum (circles) for Pd(2nm)/GaN, taken at a tunnel current of 2 nA. Also shown is a fit (solid line) to the data using a two-threshold model, which yields thresholds of 0.91 V and 1.20 V. Leakage in this sample was larger than average, decreasing the signal-to-noise for I_c measurement.

metallization. None of these attempts produced measurable collector current, even at tunnel voltages as high as 3.5 V.

All results discussed below were from contacts fabricated on material grown at Rockwell Science Center. Samples made with this material produced a measurable BEEM signal, although the magnitude was extremely small, even using thin (2 nm) metal base layers. Average observed collector current was on the order of 0.5 pA (for a 2 nA tunnel current and 1.6 V tunnel voltage), which is more than two orders of magnitude smaller than theory would predict. A tunnel current of 2 nA was used for BEEM spectroscopy and imaging in order to increase collector current and the signal-to-noise ratio. Due to the extremely low level of BEEM current, many spectra were averaged together to increase signal-to-noise.

Figure (1) illustrates such an average for a Pd/GaN sample. Also shown is a fit to the data, using the simple phase-space model [1]. Interestingly, it was necessary to allow two different thresholds in the fit to obtain good agreement with the data. The two-threshold fit to this average yields threshold energies of 0.91 eV and 1.20 eV. The extremely small signal produced Pd/GaN spectra with noticeable noise, even for averages of large numbers of spectra. The averaged spectrum in Fig. (1) is typical of all averages obtained for two different Pd/GaN samples. The average Schottky barrier height for all data was approximately 0.95 eV as measured by BEEM, although the accuracy of the threshold determination was limited by the noise level.

Imaging was also performed on these Pd/GaN samples. Figure (2) presents a STM image/ BEEM image pair



FIG. 2. STM/BEEM image pair for a Pd(2nm)/GaN sample. The topograph of the Au surface was obtained at $V=0.5$ V, $I_t=1$ nA, and the BEEM image was recorded at $V=1.8$ V, $I_t=2$ nA. I_c ranges from about 0 - 0.5 pA. Small areas of contamination provide a calibration in the BEEM image for zero current. Except for these areas, current is observed in nearly all areas. Imaged area is 196 x 150 nm.

obtained on one Pd/GaN sample. Many image sets have been recorded on each sample fabricated, and all show similar behavior. Collector current is measured in nearly all areas, although the magnitude varies from 0 to about 0.5 pA (for a 2 nA tunnel current). Small areas of contamination produced areas in the BEEM image where no collector current is measured, providing a visual calibration of for zero current, but nearly all other areas show measurable transmission.

In order to test whether samples using other metals exhibited the same small transmission, Au/GaN structures were also investigated. Preliminary characterization by conventional electrical measurement was first performed. Figure (3) shows two I-V curves taken on two different Au/GaN samples, both fabricated on the Rockwell material. Despite comparable ideality factors for the two curves, a different barrier height is extracted from each. This irreproducibility likely results from defects, and illustrates the difficulty of using macroscopic electrical probes to characterize heterogeneous materials.

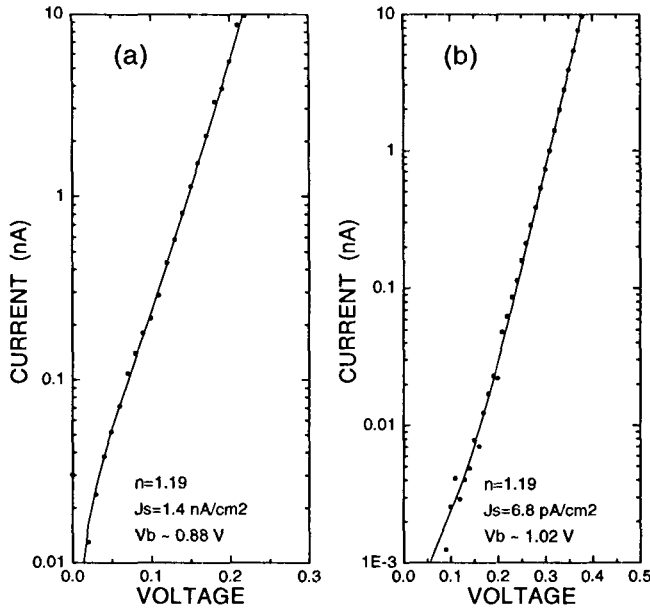


FIG. 3. Conventional macroscopic I-V curves taken on two different Au(5nm)/GaN samples. GaN material and Schottky contact preparation were identical on the two samples. Extracted barrier height values assumed an effective mass of 0.2 and an effective Richardson constant of $4\pi em^*k^2/h^3$.

Although these I-V measurements indicated the presence of defects, BEEM spectra on both of these samples (and on all measured Au/GaN samples) yielded a reproducible Schottky barrier height between 1.02 and 1.07 eV. Figure (4a) shows an average of many spectra on one Au/GaN sample. Leakage current was generally somewhat smaller for Au than for Pd, resulting in lower noise in the BEEM spectra. The higher data quality allows a more precise assignment of threshold position. For these Au/GaN samples the BEEM spectra also exhibit two thresholds. This is more apparent in Fig. (4b), where the attempted fit to a model with a single threshold resulted in poor agreement over the entire spectral range.

One problem created by the extremely small collector current is the necessity to average many spectra to obtain acceptable signal-to-noise. The capability for resolving the two thresholds is in turn reduced by this averaging process. Although signal-to-noise is improved by averaging, any variation in the energies of the thresholds at different points on the surface will produce a broadening which decreases energy resolution. Spectrum averaging also allows the possibility that a two threshold spectrum is actually a linear combination of two single-threshold spectra, obtained at different locations, and with different threshold energies. In order to rule out this possibility, individual spectra were examined. Six examples are shown in Fig. (5). Although the noise level is higher for individual spectra, it is apparent that the first threshold always occurs around 1 V, and in most cases a second threshold is apparent at approximately 1.2 to 1.3 V. However, the thresholds do appear to vary somewhat in position, possibly due to variations in strain [5] or to the presence of defects [6],

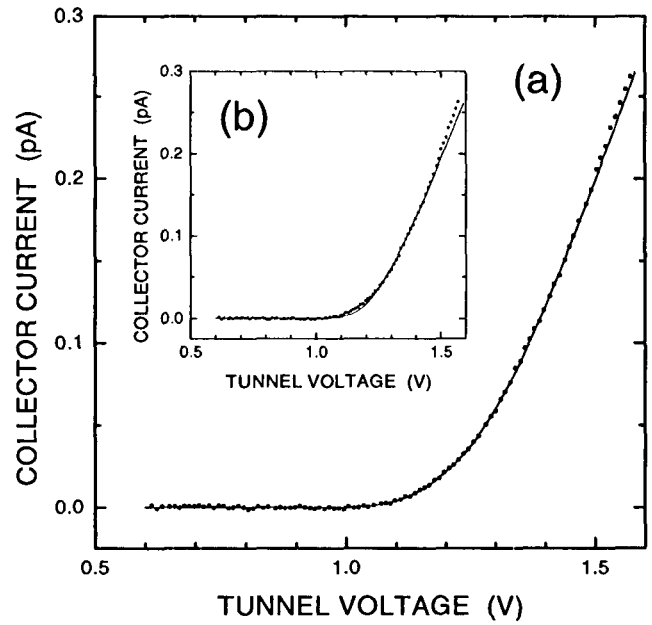


FIG. 4. BEEM I_c -V spectrum (circles) for Au(6nm)/GaN, taken at a tunnel current of 2 nA. (a) Fit (solid line) to the data using a two-threshold model, which yields thresholds of 1.06 V and 1.22 V. (b) Fit to the data assuming only one threshold, yielding a value of 1.12 V. The same data are shown in both (a) and (b).

implying that the signal averaging process is broadening the thresholds to some degree.

Figure (6a) presents a STM image/BEEM image pair obtained on one Au/GaN sample. Many image sets have been recorded on each sample fabricated, and all show similar behavior. Collector current is measured in nearly all areas, although in this image the magnitude varies from about 0.02 pA to 0.3 pA (for a 2 nA tunnel current). Individual BEEM spectra were also taken at the locations indicated by "+" symbols, and these are shown in Fig. (6b). Collector current in this image is even smaller than for most Au/GaN samples, thus signal-to-noise does not allow a meaningful fit to two thresholds. However, it is apparent that current is observed in all locations, even though the magnitude varies substantially.

The extremely small BEEM transmission observed for metal/GaN structures is unusual. GaN is a direct semiconductor, thus the small currents cannot be explained by small coupling to conduction-band minima at large parallel momentum. An insulating or heavily scattering interfacial layer might also attenuate transmission, as might strong scattering in the GaN later itself, if the effect were to backscatter most electrons into the metal layer [7]. Preliminary measurements at 77K indicate that there is not a strong change in transmission at low-temperature, arguing against temperature-dependent mechanisms such as phonon scattering.

Earlier BEEM spectra on Au/GaN by Brazel et al. [8] presented somewhat different results. These spectra also displayed two thresholds; however, in that case the measured first threshold was much lower (~ 0.7 V), and the second threshold was measured to be at approximately

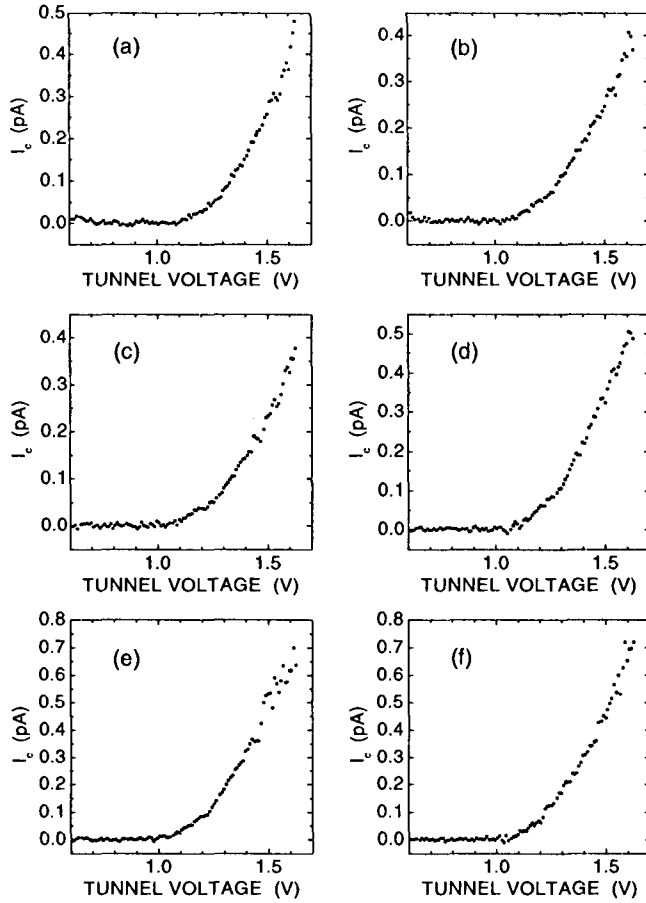


FIG. 5. Six individual I_c -V spectra taken on two different Au/GaN samples at a tunnel current of 2 nA. Although the noise level in these unaveraged spectra is high, two thresholds can usually be observed.

1.04V. It is interesting that this second threshold agrees in energy quite well with the first threshold in the present spectra for Au/GaN, and that the magnitude of the BEEM current was measured to be much larger than in the present work.

Interface transport in a defected area might produce a threshold lower in energy than that of the normal Schottky barrier height. Since the highest barrier heights measured by conventional I-V [9-11] are in excess of 1 eV, it is expected that BEEM measurements on high-quality GaN would usually produce values equal to or greater than this value. The BEEM spectra obtained here never displayed a first threshold lower than 1 V. If BEEM spectra with a threshold at 0.7 eV represent defected areas, they would have to be infrequent in order that they not dominate the I-V measurements. However, the second threshold in the prior work might then represent the Schottky barrier height energy, in agreement with the value measured in the present experiments.

It is also possible, however, that high strain might perturb the band structure by decreasing both thresholds in energy. In this case the two thresholds here and in the work of Brazel et al. would represent the same band

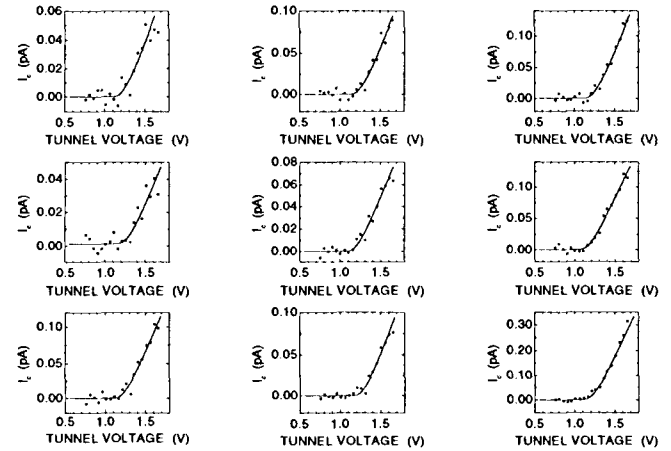
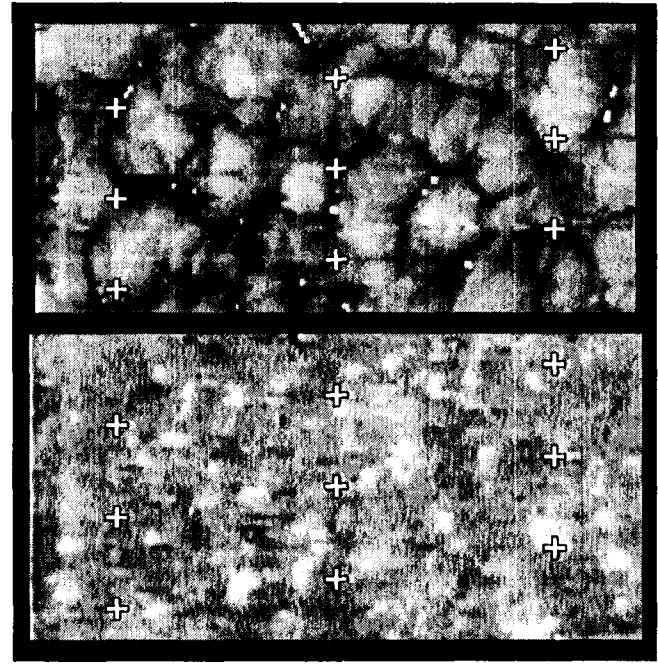


FIG. 6. STM/BEEM image pair for a Au(6nm)/GaN sample. The topograph of the Au surface was obtained at $V=0.5$ V, $I_t=1$ nA, and the BEEM image was recorded at $V=1.6$ V, $I_t=2$ nA. I_c ranges from about 0.02 - 0.3 pA, and transmission is observed in nearly all areas. Imaged area is 196 x 100 nm. Also shown are individual spectra obtained at the positions indicated by the "+" marks in the images. Here also $I_t=2$ nA. The plotted fits include only a single threshold, and are shown only to guide the eye.

minima. Large strains at the GaN/sapphire interface exist [12] due to the large lattice mismatch; the range of surface strains, however, could depend on growth conditions and methods, and might be substantially different for epilayers from different sources.

The existence of a second threshold in the BEEM spectra is unexpected, since a second conduction-band minimum is not predicted at these energies by band structure calculations. Recent calculations [13,14] only produce a second band about 2 eV above the lowest minimum Γ_1 , which is much higher than observed here. Strain effects due to the large lattice mismatch between GaN and sapphire, as described above, could strongly distort the conduction

bands[15] and perturb the splitting observed in BEEM spectra, and some degree of variation in strain and BEEM threshold would be expected.

The variation in threshold splitting will be examined more completely when samples exhibiting larger transmission are achieved. It is also important to verify that the two thresholds can be attributed to the nitride conduction-band structure. Further work on AlGaIn epilayers would determine whether a systematic change of threshold separation with Al fraction occurs, providing an indication of the mechanism for the second threshold. The observation in BEEM measurements of zero transmission on some GaN layers and small transmission on others will be investigated further in future experiments. This lack of transmission, and the extremely small BEEM currents observed in the transmitting samples, are possibly indicative of the same attenuation mechanism. This suggests that optimization of the GaN layers in some respect (most probably defect-related) might produce a further increase in transmission. Experiments involving the effects of annealing will also be performed.

In conclusion, BEEM spectroscopy and imaging have been performed on Pd/GaN and Au/GaN Schottky barrier structures. These experiments yield a value of Schottky barrier height which is reproducible and occurs at all observed positions at the metal/GaN interface. A second threshold is also reproducibly observed in the BEEM spectra of both structures, raising the possibility of a secondary conduction-band minimum about 0.2 - 0.3 eV above the primary minimum. BEEM imaging reveals transmission in most areas of the interface, although the magnitude is unusually small and varies strongly, a feature that also appears with both metals. This observation, together with the lack of measurable interface transmission when using other GaN material, suggests a persistent attenuation mechanism which may be defect-related. Further work on other GaN material, as well as BEEM measurements on AlGaIn layers, are planned to clarify these issues.

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